1   <u>Title of the Invention</u>

2

3   "Control of Etch and Deposition Processes"

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5   <u>Field of the Invention</u>

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7   This invention relates to the control of etch and

8   deposition processes in the manufacture of

9   semiconductor devices, microelectronic machines

10   (MEMs), and waveguides.

11

12   <u>Background to the Invention</u>

13

14   It is well known that interferometric techniques can

15   be applied to determining the endpoint in thin film

16   deposition or etch. However, these techniques have

17   been limited in their application to feature sizes

18   of a few microns or greater, since the probe light

19   is incapable of resolving smaller structures due to

20   the diffraction limit of the probe light.

21   Contemporary feature structures are becoming so

22   small that they are less than the diffraction limit

1 in dimension and the prior art techniques are

2 becoming less useful and applicable because of this

3 limit.

4

5 An object of the present invention is accordingly to

6 provide a method of monitoring semiconductor

7 processes such as etch and deposition involving

8 small feature sizes. Desirable and achievable

9 outcomes of proper use of these techniques are

10 elimination of the etch stop layer in dielectric

11 etch, an improvement in control of shallow trench

12 isolation etch, an improvement in gate oxide etch,

13 an improvement in gate etch, an improvement in

14 trench etch for memory applications, and an

15 improvement in gate spacer etch. The invention is

16 also applicable to the control of a range of micro-

17 machining applications.

18

19 Brief Description of the Invention

20

21 The invention provides a method for improved control

22 of etch or deposition in a semiconductor

23 manufacturing process to produce a structure having

24 a small feature size.

25

26 A spectrally narrow illumination source is provided

27 at a selected wavelength or wavelengths, from which

28 an optical probe measurement beam is generated.

29

30 An article undergoing processing is illuminated with

31 said beam, the article having within the area of

32 illumination an ordered feature arrangement having a

feature size of the same order as the structure of
the device to be fabricated and being arranged in a
regular pattern the pattern exhibiting a given
feature spacing or a given set of feature spacings.

Where the illumination source provides a beam normal
to the surface of the article being processed, each
said wavelength within the measurement probe beam is
chosen such that a whole number of wavelengths
compounds to a length equal to within +/- 30% of one
of the feature spacings.

Where the illumination source provides a beam that
is not normal to the surface of the article being
processed, each wavelength within the measurement
probe beam is selected such that a whole number of
wavelengths compounds to a length equivalent to
within +/- 30% of the projection of one of the
feature spacings on a plane normal to the
measurement probe beam.

An oscillation of a polarisation component in the
light beam reflected from the article being
processed is detected as the etch or deposition
progresses, which oscillation is derived
substantially from anomalous reflection or Rayleigh
resonance at the feature arrangement resulting from
the illumination. The oscillation is used to detect
or predict the desired endpoint or monitor the
progress in real time of the etch or deposition.

1 The ordered feature arrangement may be a test

2 structure applied to the article for the purpose of

3 monitoring the process, or may comprise structural

4 features of the desired article itself.

5

6 Any overlying mask is preferably substantially

7 opaque to the wavelength of the illumination source,

8 and preferably the ordered feature arrangement has a

9 ratio of feature open to etch to features masked

10 from the etch of between 5% and 95%.

11

12 From another aspect, the present invention provides

13 apparatus for use in a semiconductor manufacturing

14 process, the apparatus comprising:

15   a vacuum enclosure;

16   a workpiece location within the enclosure for

17 locating a semiconductor workpiece to be processed

18 to produce a structure having a small feature size,

19 said semiconductor workpiece having an ordered

20 feature arrangement having a feature size of the

21 same order as the structure to be produced and being

22 arranged in a regular pattern having a given feature

23 spacing or a set of feature spacings;

24   a spectrally narrow illumination source

25 producing light at one or more wavelengths within

26 30% of a whole number of wavelengths of a size equal

27 to the projection on a plane normal to the

28 illumination beam of said feature spacing or feature

29 spacings;

30   optical projection means cooperating with the

31 light source to produce an optical probe measurement

32 beam directed to said workpiece location;

1   optical detection means arranged to detect

2 an oscillation of a polarisation component in the

3 light beam reflected from the article being

4 processed which is derived substantially from

5 anomalous reflection or Rayleigh Resonance at the

6 feature arrangement resulting from the illumination;

7 and

8   data processing means arranged to use the

9 oscillation to detect or predict the desired

10 endpoint or monitor the progress in real time of the

11 etch or deposition.

12

13 Other preferred features and advantages of the

14 invention will be apparent from the following

15 description and the claims.

16

17 Detailed Description of the Invention

18

19 An embodiment of the invention will now be

20 described, by way of example only, with reference to

21 the drawings, in which:

22   Fig. 1 is a cross-section of a typical prior

23 art semiconductor construction;

24   Fig. 2 is a front view of a silicon wafer

25 showing structures used in the method of the

26 invention;

27   Fig. 3 is a cross-section of part of Fig. 2 to

28 an enlarged scale;

29   Fig. 4 is a schematic of an apparatus embodying

30 the invention; and

31   Fig. 5 shows part of the apparatus of Fig. 4 in

32 greater details.

1

2   A typical section of the etched dielectric for the

3   semiconductor conductor deposition scheme known as

4   'Damascene' is shown in profile in Figure 1.

5   Typically the structure is etched down to an etch

6   stop layer 1 which layer provides for a slowing down

7   of the etch so that the etch may be terminated by

8   reference to time or alternatively the

9   distinguishing chemical composition of the etch stop

10   layer 1 may be determined by reference to specific

11   wavelengths of light emitted within the plasma used

12   to carry out the etch.

13

14   It is desirable to optimise the performance of the

15   semiconductor device by eliminating the etch stop

16   layer and decreasing the geometry of the device and

17   improving the permittivity of the dielectric

18   material, and decreasing the total number of process

19   fabrication steps.

20

21   It is known (Ref: FR-2718231) that interferometric

22   techniques which derive measurements from

23   interfering optical signals (Figure 2) reflected

24   from the top of the etched surface 2, the top of the

25   mask 3, the bottom of the etched film 4, and the

26   bottom of the mask 5 can yield data throughout the

27   etch. Furthermore, it is known (Ref: US 6,226,086

28   B1) that processing the data relative to a

29   mathematical model of the physical situation

30   provides additional useful information so that

31   remaining thickness and etch rate can be determined

32   with high accuracy providing an improvement in

1 process control and possible elimination of the need

2 for an etch-stop layer.

3

4 An analogous situation exists where a film is being

5 deposited rather than etched.

6

7 It is common practice to deliver the optical signal

8 as a focussed spot in such a way that the

9 illumination substantially falls on the surface

10 being etched. Although common this practice has the

11 disadvantage that the spot size is practically

12 limited by diffraction to about 5 microns. This size

13 is no longer compatible with the development of

14 semiconductor, MEMs and waveguide devices, which are

15 now below one micron in feature size.

16

17 An alternative is to illuminate a larger area: this

18 has the advantage of illuminating a number of

19 structures and some diffraction effects will provide

20 a modulation of the signal, which can enable

21 endpoint detection. However, with known techniques

22 very little of the signal couples into the

23 structures and the etched films and the endpoint

24 signatures are consequentially weak and ill defined.

25

26 It is a prime objective of this invention to provide

27 a means for efficient coupling of an interferometric

28 probe beam into the combined structure of mask,

29 etched film and/or substrate by using an

30 illumination means with a wavelength or wavelengths

31 which are deliberately chosen so that the mask and

32 film into which the small structures are to be

1 etched maximise their interaction with the

2 illumination and thus continue to provide strong

3 modulation by means of interference between the

4 incoming and reflected waves even though the

5 structures themselves are below the diffraction

6 limit of the illuminating probe beam.

7

8 Proper choice of wavelength involves consideration

9 of the structure dimension, its orientation with

10 respect to the polarisation planes of the probe

11 beam, and consideration of its spacing and repeat to

12 the structures surrounding it. If mathematical

13 analysis does not yield a suitable wavelength choice

14 using the repetition of structures present naturally

15 (that is, arising from the desired structure design)

16 on the substrate, then the invention provides for a

17 specific test structure to be placed on the

18 substrate with a repetitive structure which can be

19 easily analysed. Such test structures can

20 conveniently be placed in the scribe lines

21 conventionally present on semiconductor wafers. If

22 a test structure is used, it is selected to have a

23 geometry which simultaneously meets the requirements

24 of optimising the coupling to the structure at a

25 feature size that is fully representative of the

26 feature size to be monitored during the thin film

27 etch or deposition process.

28

29 This invention exploits these coupling effects to

30 provide measurement during the etch or deposition

31 process. The mask (if used) and substrate materials

32 are opaque to the probe wavelength which is chosen

1   to be close to the separation of the features as
2   projected onto the plane normal to the incident
3   beam; 'close' in this context is taken to be within
4   30%. Under these conditions the feature size itself
5   can be as small as 1/10 of the illuminating probe
6   wavelength. A cooperative effect of the
7   illuminating radiation governed by the separation of
8   the features being equal or close to the wavelength
9   or wavelengths of the illuminating probe results in
10 an interference reflection signal which is modulated
11 by the etch depth. This effect predominantly
12 interacts with only one of the polarisation
13 components of the illumination, and by separating
14 the reflected beam into its polarisation components
15 considerable improvement in signal quality can be
16 obtained by referencing one polarisation mode to the
17 others. This feature can also be used to remove
18 undesirable modulation of the detected signal by
19 etch of the mask rather than etch of the feature
20 which it is desired to detect.
21
22 In the case where the etched feature contains a
23 substantially transparent film overlying a
24 substantially opaque film or substrate material, the
25 solution of Maxwell's equations at the surface shows
26 that modulation of the interference signal occurs
27 which indicates remaining thickness of the
28 substantially transparent film. This remaining
29 thickness is a very desirable measurement as it
30 permits the endpoint of an etch part-way through a
31 film as is required for dielectric etch in the case
32 where an etch stop layer is not provided, or for the

1   process of slowing down an etch before the critical

2   endpoint so as not to break through a thin residual

3   film (as in the process known as 'soft landing' for

4   gate etch), or in circumstances where it is

5   desirable to change the etch conditions before the

6   final process endpoint in order to optimise the etch

7   by, for example, changing the degree of sideways

8   etch for gate width optimisation purposes.

9

10   Consider the example wafer structures shown in

11   Figure 2. The structures 6 that it is desired to

12   etch have a line width of 0.2 microns.

13

14   The test structure 7 that would have previously been

15   required has a dimension of 10 microns. This would

16   accommodate a focussed spot diffraction limited at 5

17   microns from a monitoring interferometer, but the

18   large size of the feature would mean that the etch

19   process would proceed at a different rate in the

20   test feature from that within the structure that

21   requires to be manufactured. As such the monitoring

22   technique will not return a useful measure.

23

24   Now consider the array of features shown in the test

25   structure 8 on the example wafer. These have a

26   feature size (0.2um) that is representative of the

27   size of the process feature 6 that requires to be

28   monitored, but in addition they have a geometrical

29   arrangement that has been carefully chosen to

30   optimise coupling of the incident interferometric

31   monitor beam into the region below the mask. It will

32   be appreciated that a suitable arrangement may

naturally follow from the circuit design or other design on the substrate as an alternative to optimising the effect by use of a test structure.

Fig. 3 represents a cross-section of the test structure 8. This has features 20 with a feature size (0.2um in this example) which is representative of the size of the process feature 6 (Fig. 2) which requires to be monitored. In addition, the spacing between features 20 is chosen such that the repeat distance 22 is equal to the wavelength λ of the inspecting beam or to a multiple thereof 2λ, 3λ etc. Alternatively, as discussed above the wavelength may be chosen to be up to 30% away from the $n\lambda$ value.

The foregoing assumes that the inspection beam will be normal to the surface of the wafer. Where this is not the case, the distance 22 is increased such that its projection on the plane normal to the inspection beam is equal to λ, 2λ, 3λ, etc

Provided that the etched film and the mask are substantially opaque to the incident wavelength, and if the features occupy a sufficient proportion of the surface area (between 5% and 95% of the illuminated area), the incident radiation will couple with the resonant volume apparent to the illuminating radiation and yield an interferometric measure of the etch or deposition which can then be used to determine the process endpoint or to control process rate and uniformity.

1   One apparatus for carrying out the invention is

2   illustrated in Fig. 4. The apparatus includes an

3   enclosure 40 which can be evacuated via an exhaust

4   line 42 by a vacuum pump (not shown). A support 44

5   locates a semiconductor wafer 46 in line with a

6   window 47 for transmission of optical beams. It

7   will be understood that the apparatus is provided

8   with means for supplying etchant gas, plasma, or

9   other processing media in conventional manner.

10

11   A light source 48 supplies monochromatic light via a

12   fibre optic cable 50. The light source 48 may be a

13   single frequency laser, a tuneable laser, or a

14   wideband light source interfaced to a wavelength

15   selector such as one or more filters.

16

17   The fibre optic cable 50 links the light output to

18   an optical head assembly 52 shown in more detail in

19   Fig. 5. The optical head assembly includes lenses

20   54 and beamsplitters 56 to cause an optical probe

21   beam 58 to illuminate the wafer 46 at right angles

22   to the plane of the wafer 46, and to direct the

23   reflected light to a detector 60. A camera 62 may

24   optionally be provided to assist the operator in

25   directing the beam 58.

26

27   The optical head assembly may be mounted on

28   translation stages and gimbals (not shown) in known

29   manner, so that the beam can be adjusted in position

30   and angle.

31

The detector 60 provides an electrical output signal representative of the reflected optical signal, which is passed to a signal processing means 64 to provide a process control signal 66. The signal processing means 64 may conveniently comprise analog-to-digital conversion followed by numerical processing. Suitable forms of apparatus for detecting the reflected signal and processing the detected signal are well known in the art and not described in detail herein.

As discussed above, the detector 62 has the function of comparing one polarisation in the reflected beam at right angles to the plane of the wafer with the cross polarisation. In the conditions described, there is a cooperative effect known as 'anomalous reflection' or 'Rayleigh Resonance' and the reflection for the one polarisation undergoes oscillations with the oscillation representing the depth of the etch.

The basic purpose of the signal processing is to compare the real-time performance with a model of the desired process, which model may be derived by mathematical analysis or from a trial run which is known to have produced an acceptable result.

The signal processing may, in one example, comprise applying a shape or pattern recognition algorithm to the data stream. In a preferred form, the data stream is first subjected to digital filtering using a digital filter applied to one or more time windows

as the signal develops, the digital filter having
first been derived from a mathematical prediction of
the signal behaviour.

The apparatus may be used to measure depth of etch,
remaining film thickness, rate of etch, and a figure
of merit giving an average width of etch. Such
measurements can be used to control the progress of
the etch process; indicate the endpoint of the etch;
give early warning of the endpoint approach so that
the etch can be slowed down or the chemistry of the
etch changed to fine-tune the process (commonly
called a 'soft landing'); or to permit the etch to
be stopped part-way through a film, eliminating the
requirement for an etch stop layer.

The invention thus provides a means for monitoring
and determining the endpoint of the etch and
deposition processes in situations where the feature
size is small in relation to light beams which can
be practically provided.